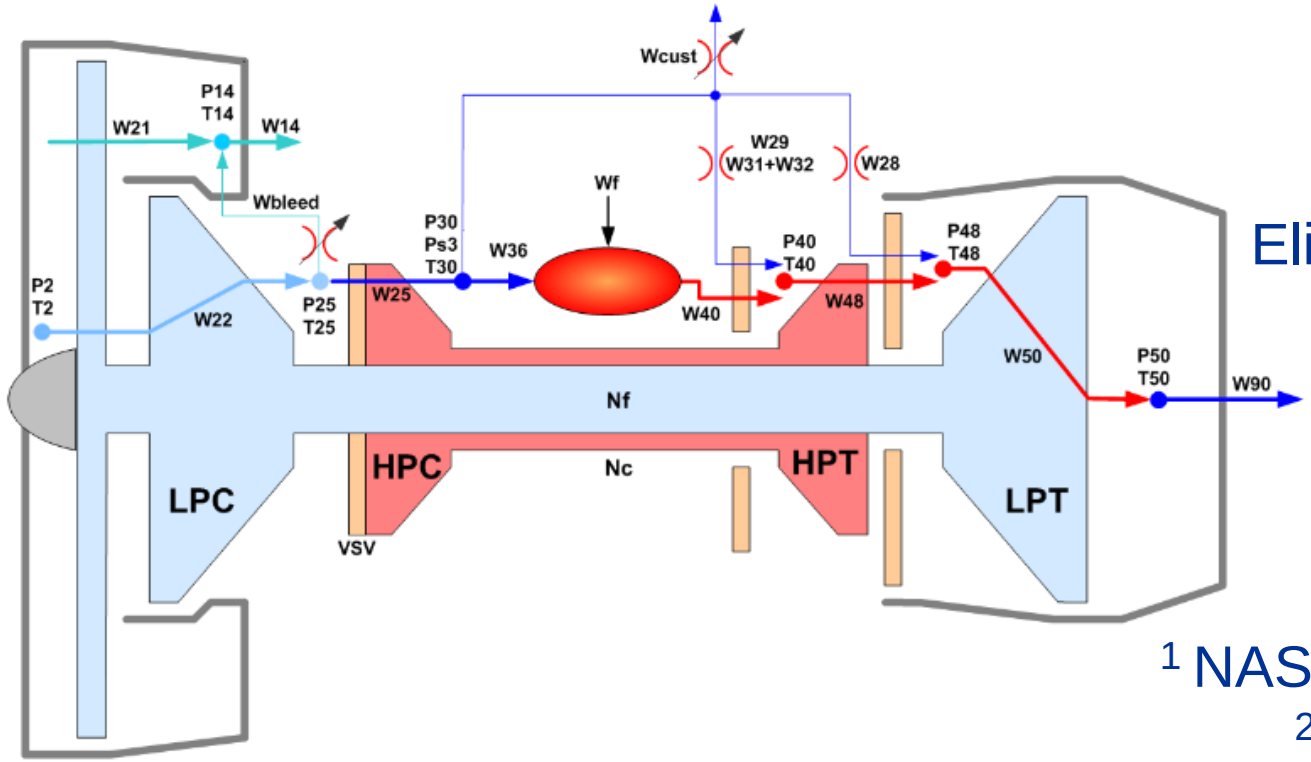
Benchmarking model variants in development of a hardware-in-the-loop simulation system



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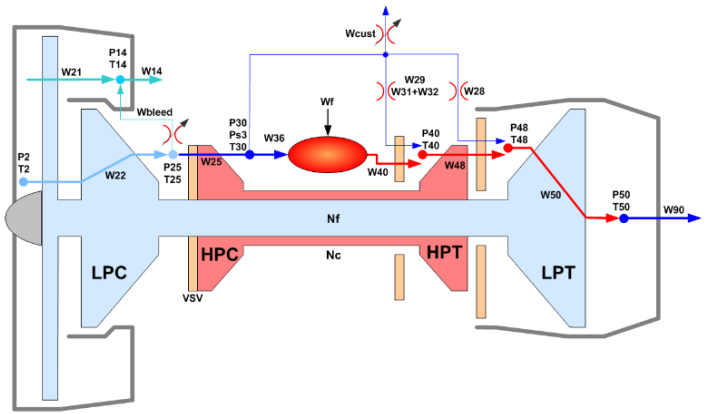
Overview

- Motivation and goals
- Control system model enhancements for hardware-in-the-loop simulations
- Benchmarking results
- Conclusions

Motivation and Goals

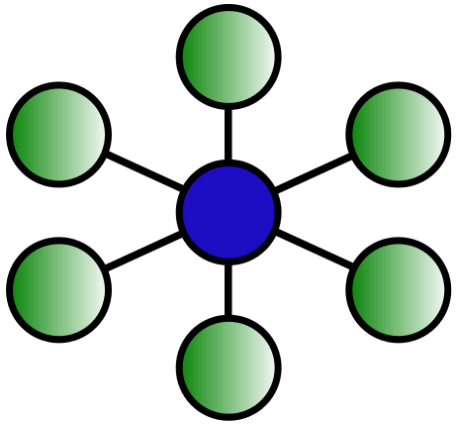
- Develop C-MAPSS40k engine model to better represent a HIL system
- Distributed Engine Control Working Group (DECWG) formed to build standards and explore the capabilities of distributed engine control
- One of NASAs contributions: conversion of C-MAPSS40k to a distributed model to enable exploration of distributed engine control
- Allows for the exploration of advanced engine control systems
  - Controls to compensate for information loss
  - Model based controls
  - Requirements exploration



Centralized vs. Distributed Control

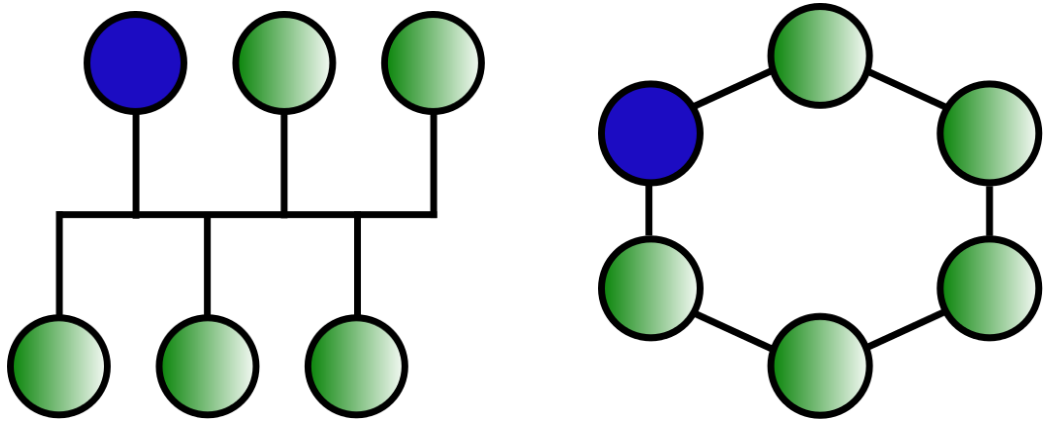
Centralized & Analog

- Simultaneous data availability
- Dedicated cable for each node
- A/D handled by central node
- Analog sensor/actuator interfaces prevent easy replacement & alternative sourcing of components



Distributed & Digital

- Sequential data availability
- A/D imbedded in the smart node
- Drop-in component compatibility
- Packet delay
- Packet loss
- Packet corruption

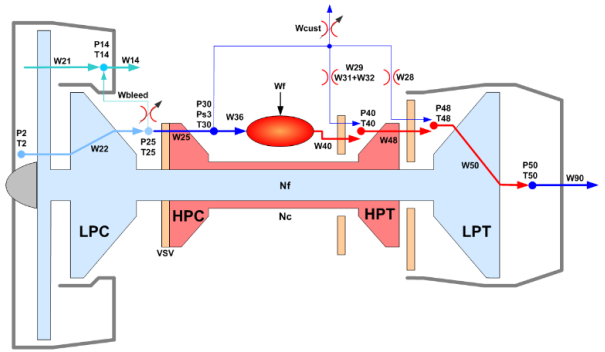


Controller Models

- Baseline: C-MAPSS40k out of the box, 1 computer

Baseline C-MAPSS40k

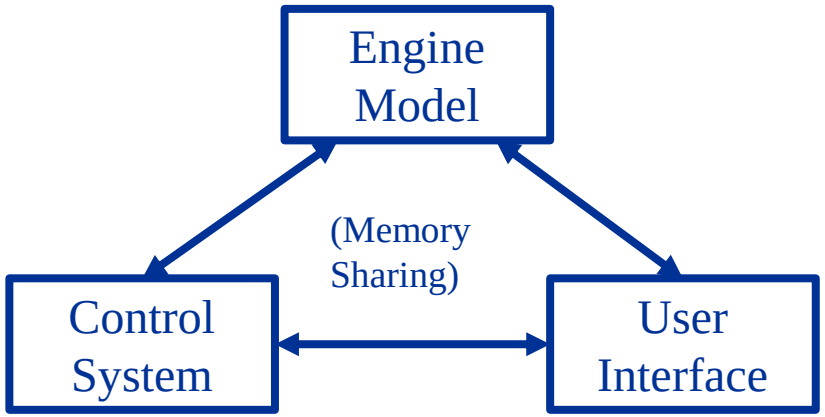
Engine Model
Control System
User Interface



Several new configurations were compared to the original C-MAPSS40k:

- Unstructured
- Distributed
- Networked
- Processor-in-the-Loop

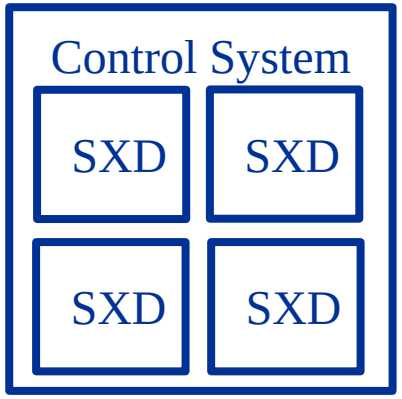
Controller Models - Unstructured

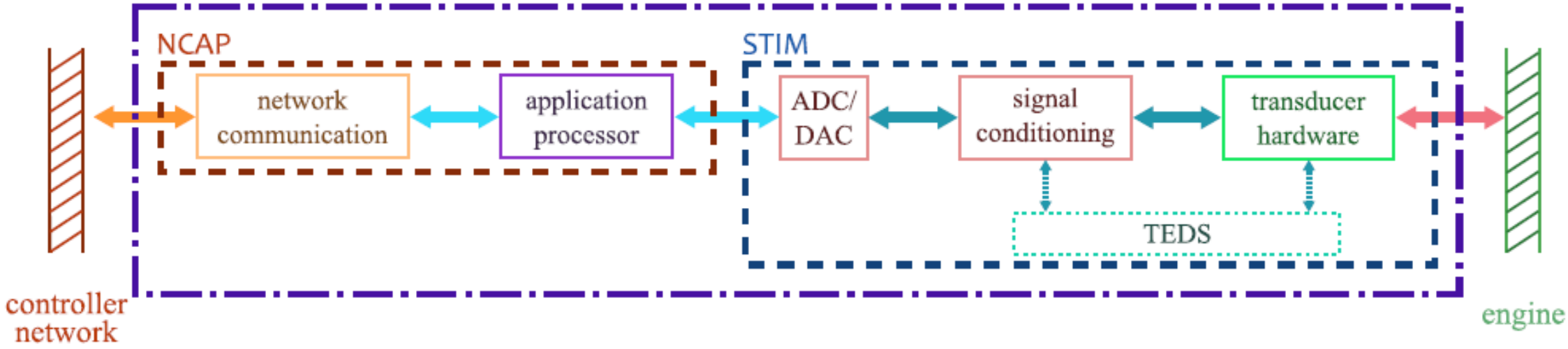


- Baseline C-MAPSS40k with independent models for control and engine plant
- UDP Ethernet network used to transparently share information between models
- Modular engine model
- Causes minimum of one time step lag between models

Smart Transducer Model (SXD)

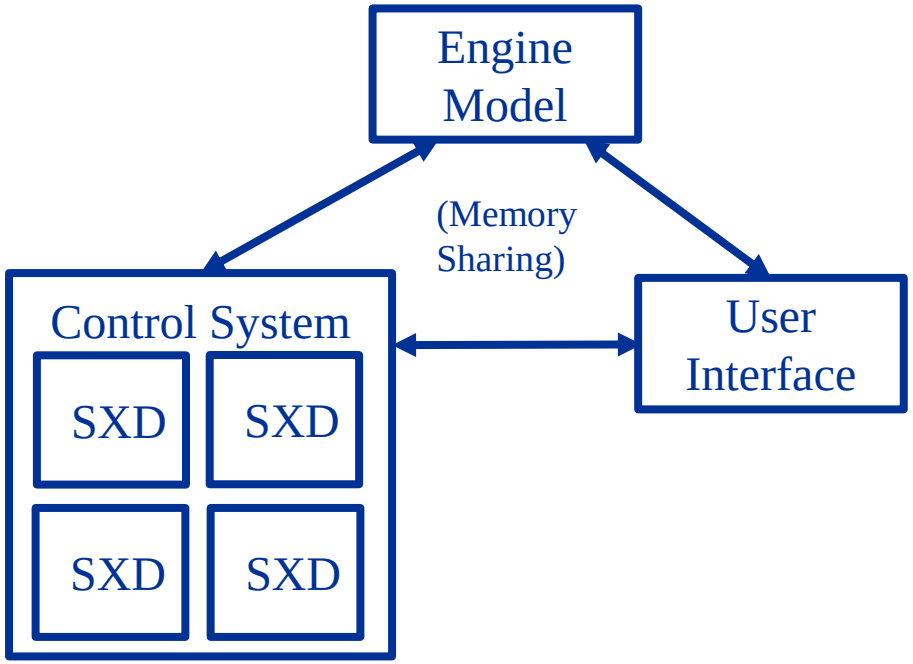
- Network Capable Application Processor (NCAP)
  - Network communication
  - Application interface to STIM
- Smart Transducer Interface Module (STIM)
  - Analog to Digital and Digital to Analog converter
  - Signal conditioning
  - Interface to transducer





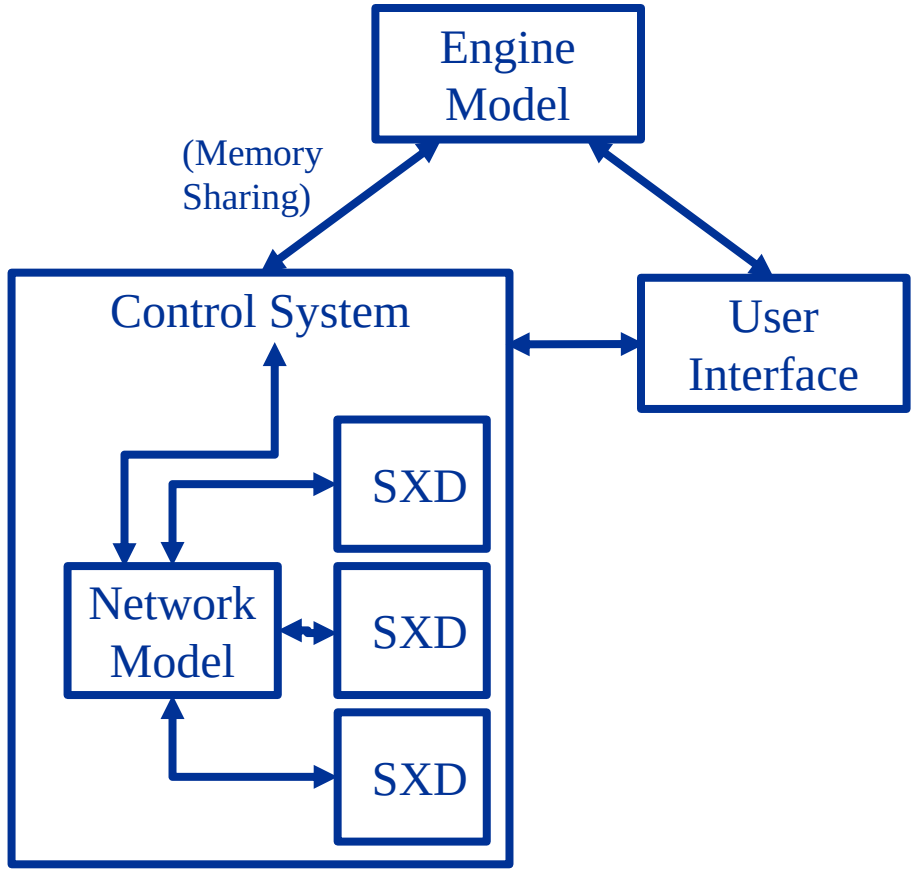
Controller Models - Distributed

- Enhanced fidelity of control elements by inclusion of smart transducer models (SXD)
- SXD models include quantization effects of 14 bit A/D conversion
- Increased computational complexity and increased errors due to quantization



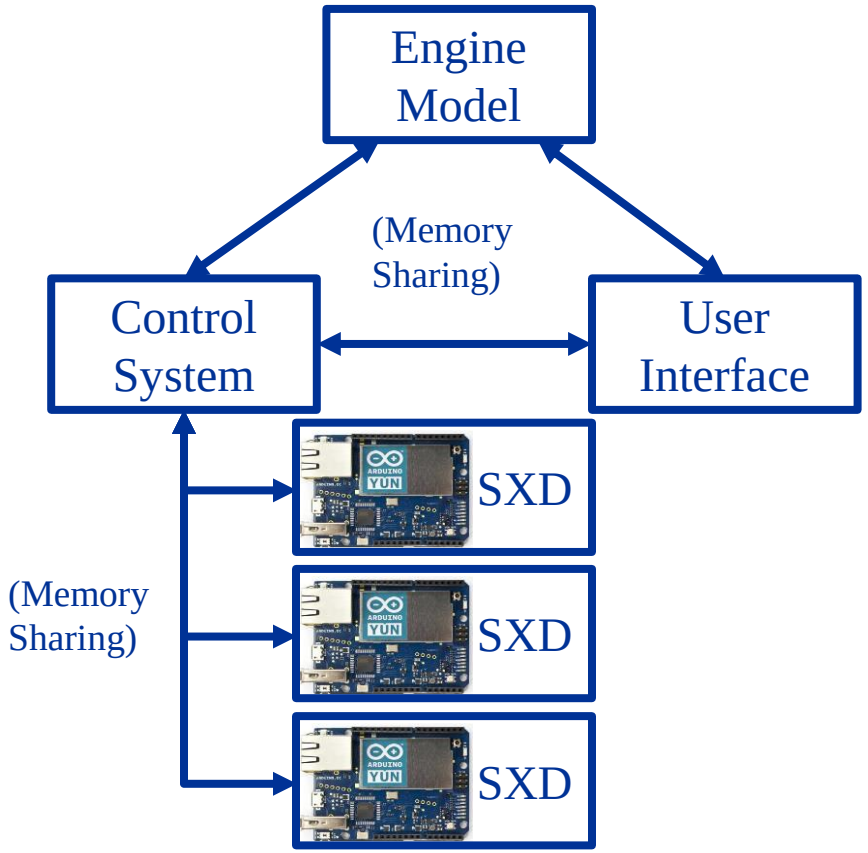
Controller Models - Networked

- Bulk network model limits communication between control system and SXD models
- Model includes packet loss and packet delay effects as settable percentages
- Increases simulation time
- Not as detailed as a packet level network model

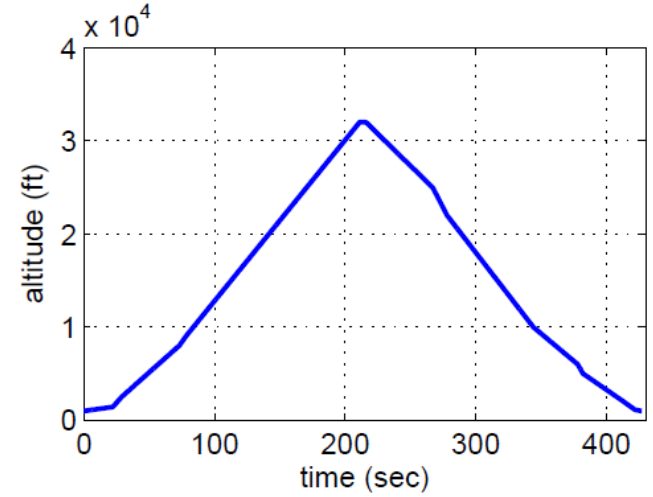


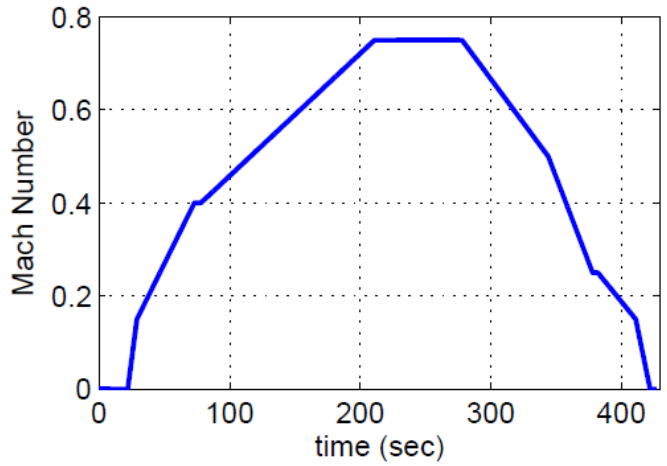
Controller Models – Processor-in-the-Loop

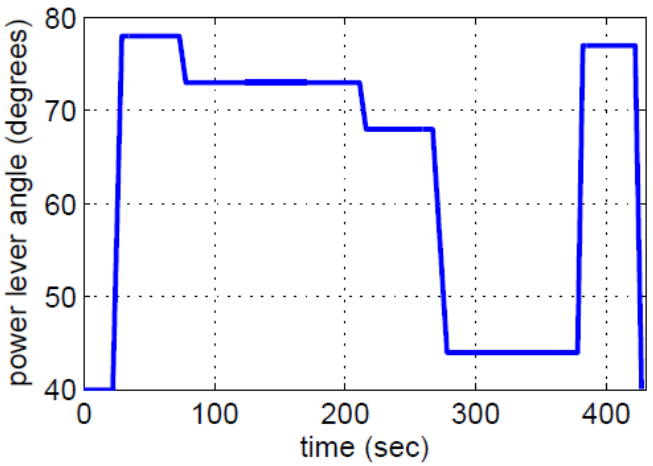
- Integration of SXD models into microcontrollers
- Ethernet UDP network used to communicate between control system and SXD models
- Better simulates processor limitations in SXD models
- Increase command / response latency due to message buffering issues in each system

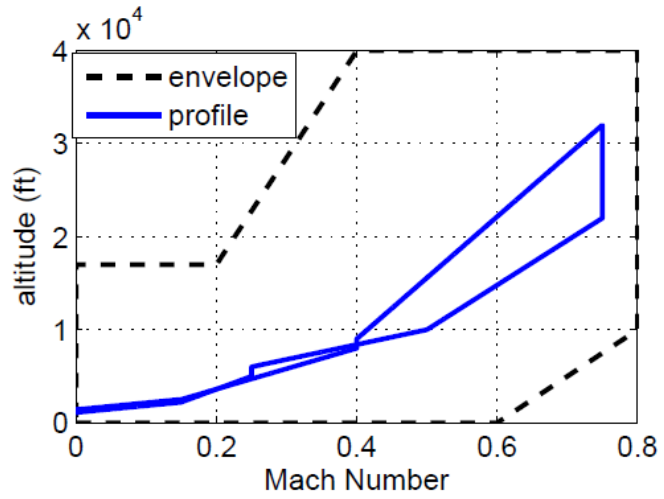


Test Profile

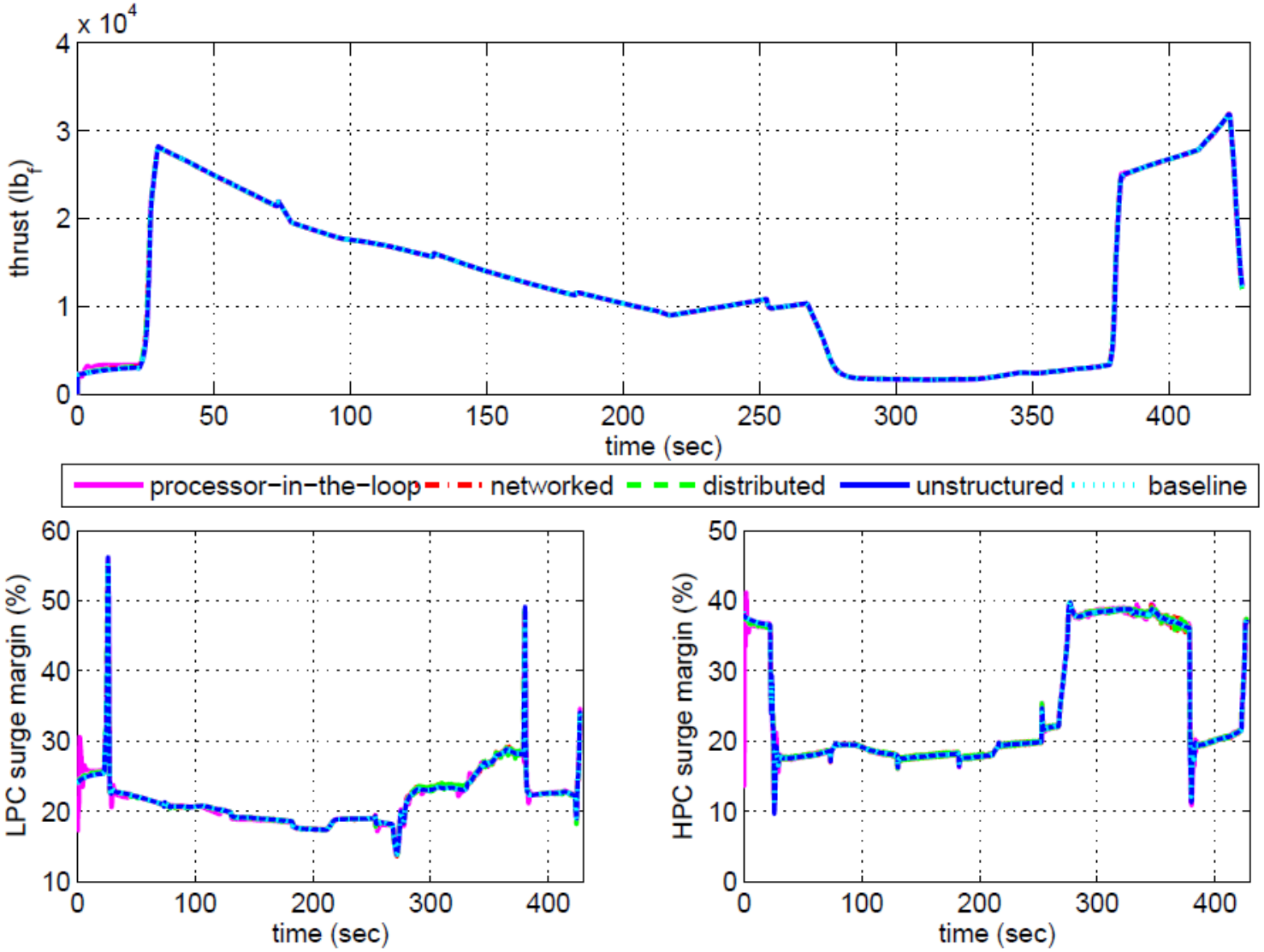




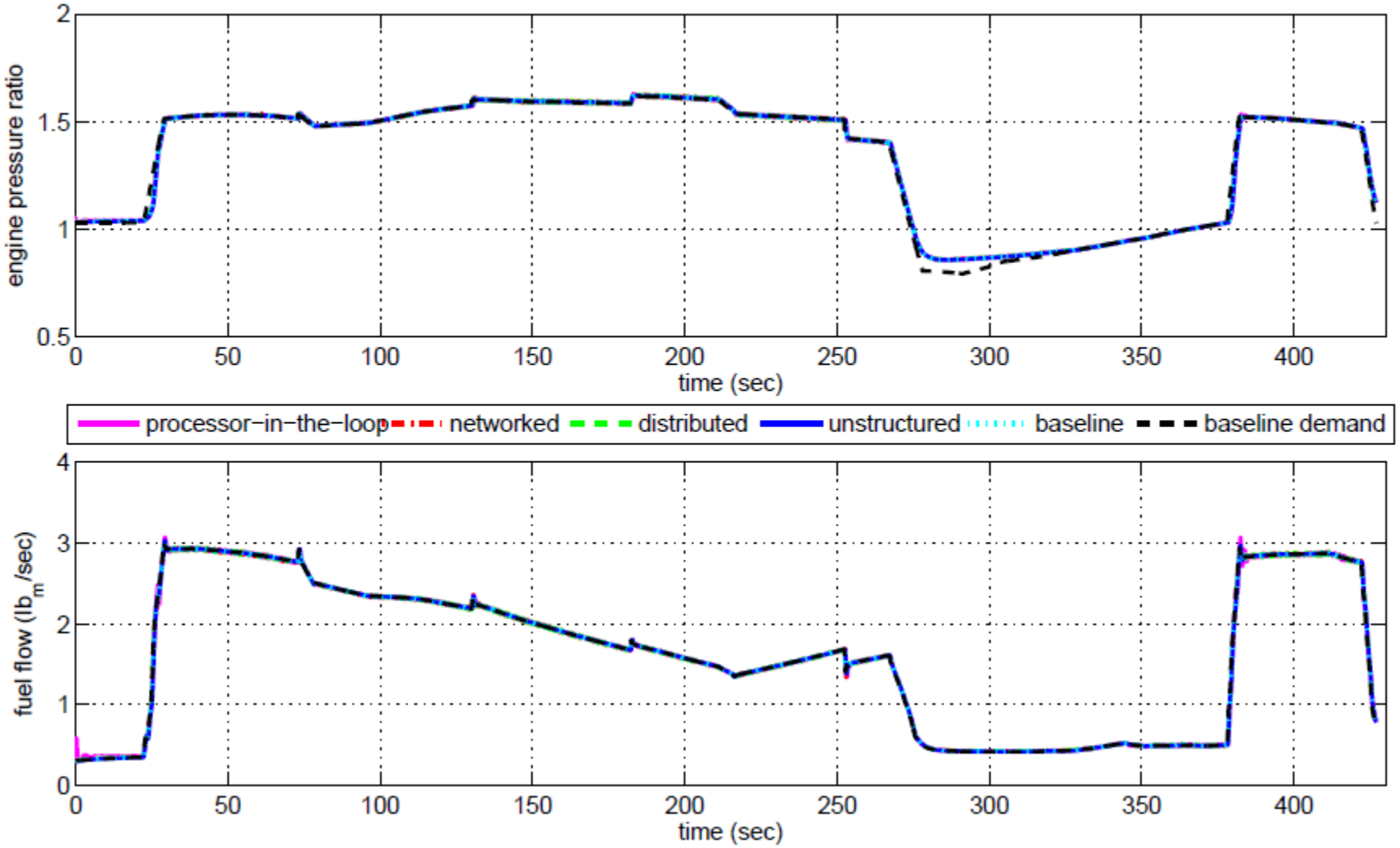




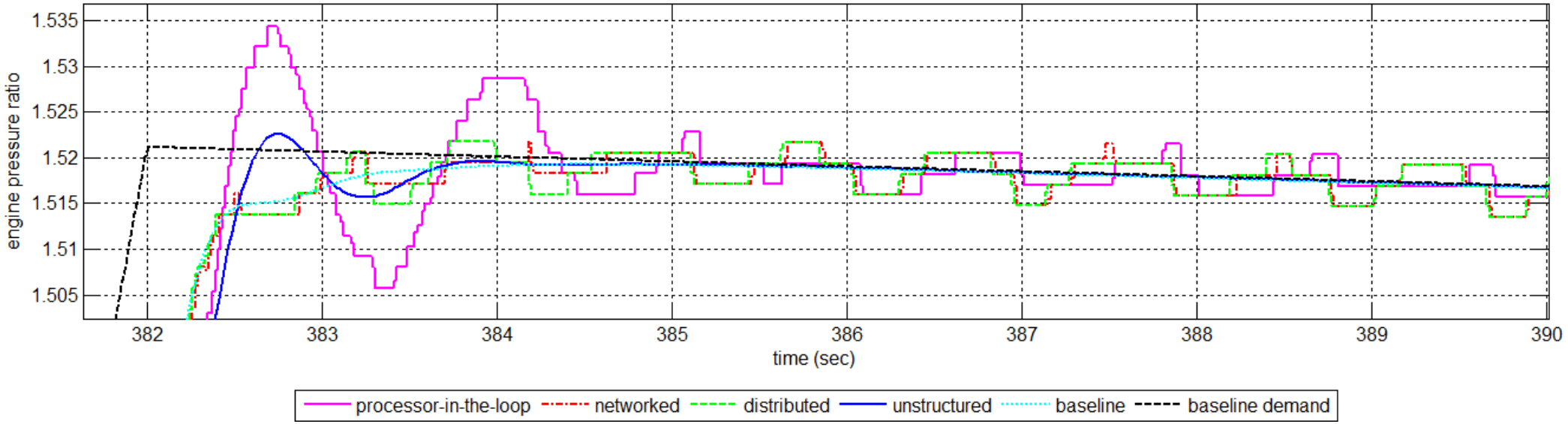
Benchmarking Results - Thrust



Results – EPR demand and Fuel Flow

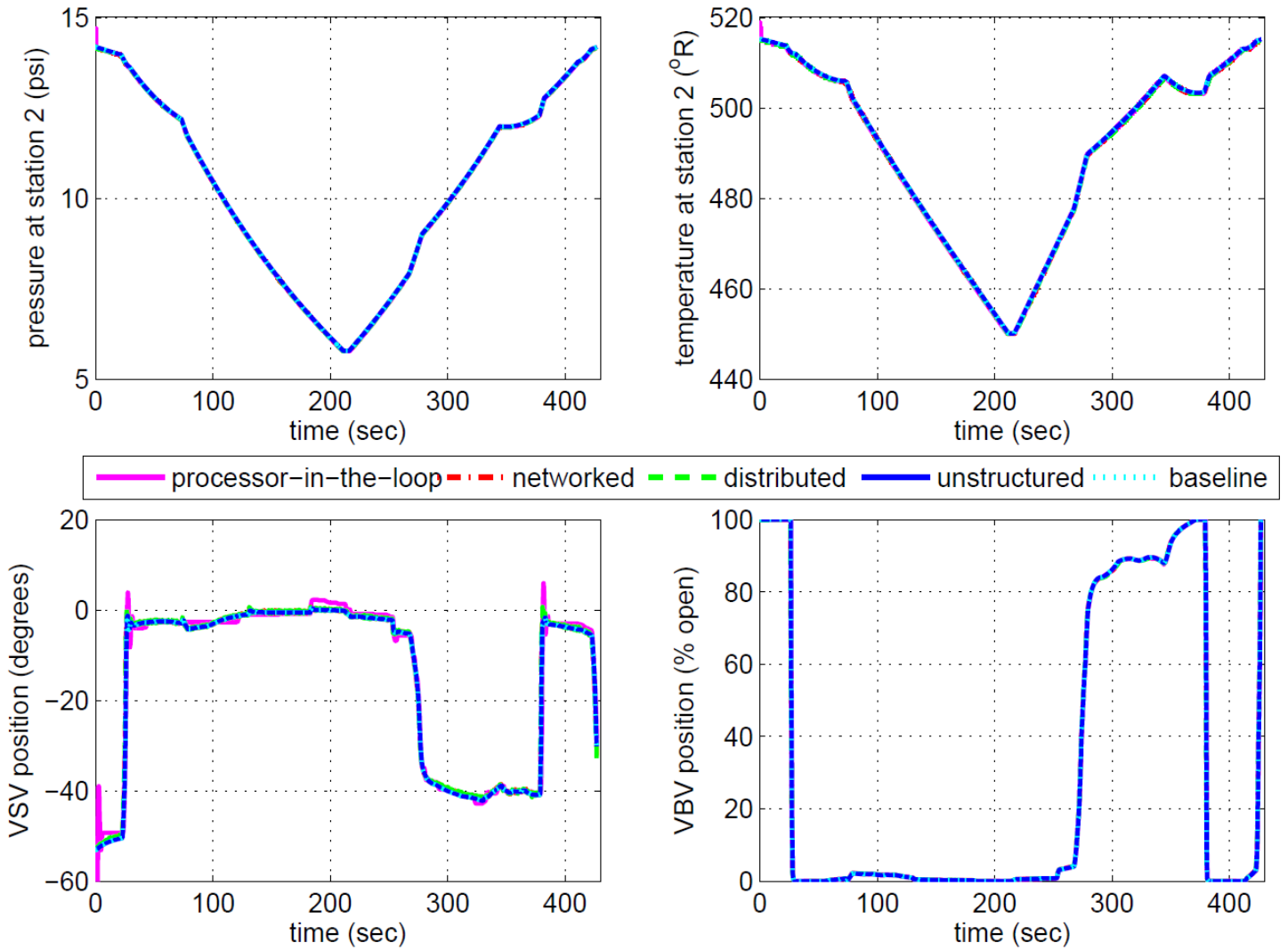


Results – EPR demand



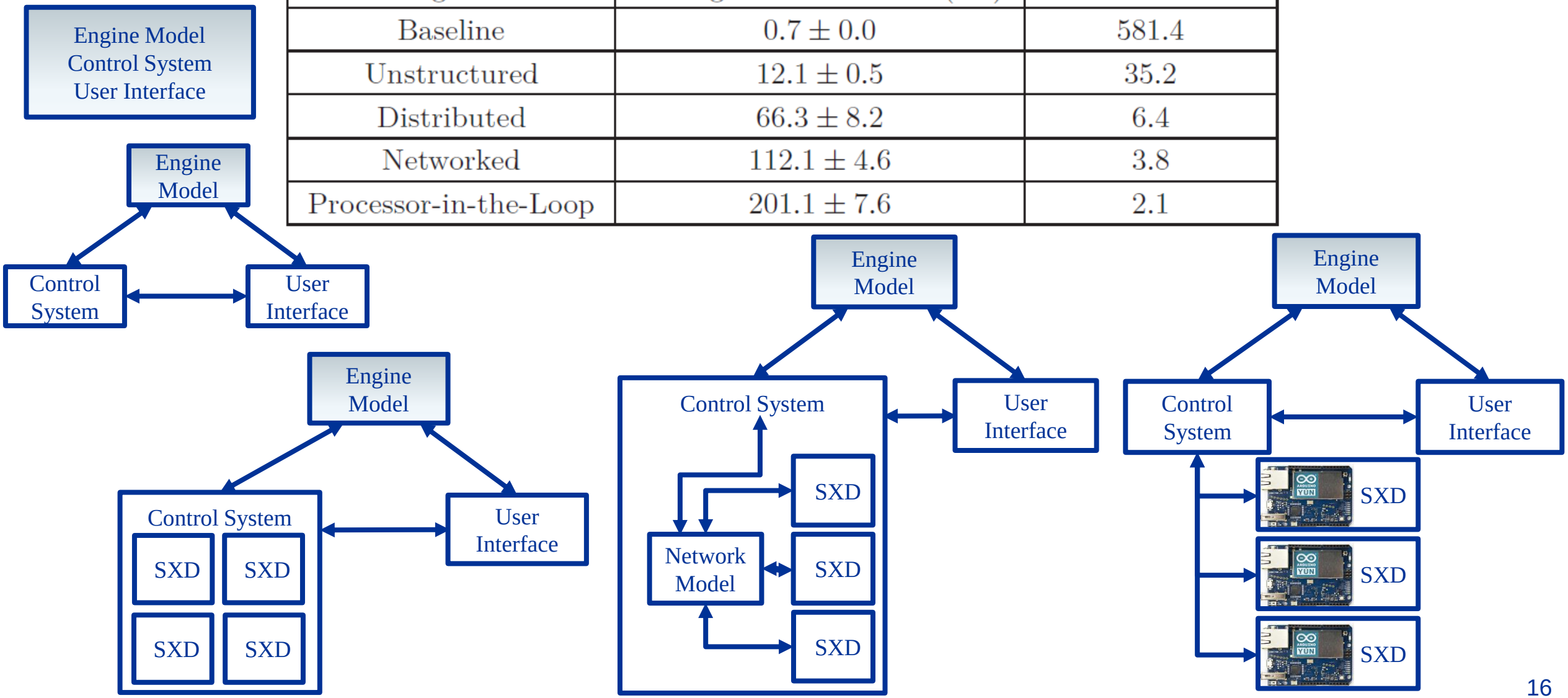
- Simulations with quantization clearly visible
- Quantization effects cascade from the sensors into the control system and then into the actuator commands
- Simulations with 8 bit quantization was unable to converge

Benchmarking Results



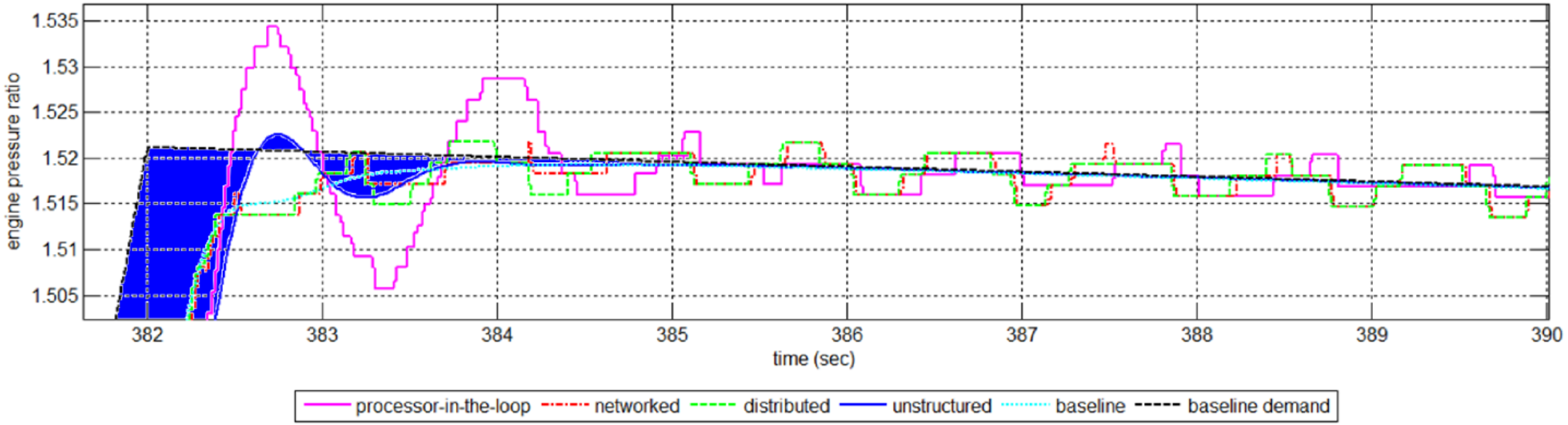
Average Benchmarking Run Times

Configuration	Average total run time (sec)	Real-time factor
Baseline	0.7 ± 0.0	581.4
Unstructured	12.1 ± 0.5	35.2
Distributed	66.3 ± 8.2	6.4
Networked	112.1 ± 4.6	3.8
Processor-in-the-Loop	201.1 ± 7.6	2.1



EPR Tracking Error

Configuration	Percentage Mean Absolute EPR Tracking Error
Baseline	1.047 ± 0.00
Unstructured	1.091 ± 0.001
Distributed	1.197 ± 0.009
Networked	1.198 ± 0.008
Processor-in-the-Loop	1.227 ± 0.004



Summary & Conclusions

- Five Configurations of C-MAPSS40k Engine Model Tested
- Each configuration added additional complexity to the simulation
- Small (>1%) differences between configurations
- This shows that the implementation is solid
- These new configurations will be used to study real-time and network model integration to help us answer important questions like:
  - How much bandwidth do I need to perform minimum control operations
  - How much processing capability do I need on my smart nodes to ensure safe operation (this may increase with decreasing bandwidth because you need more local limiters)

Questions?

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Future Work – Network-in-the-Loop